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Multistatic Nearfield Imaging Radar for Portal Security Systems Using a High Gain Toroidal Reflector Antenna

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Abstract—A Toroidal reflector, consisting of a tilted ellipse rotated about the vertical axis, provides for multiple, overlapping high-resolution nearfield beams that form multi-view, true multistatic mm-wave imaging for security applications. Modeled results indicate the PSF on a torso target is wide and short, allowing for quickly computed 2D images which can be stacked to reconstruct detailed 3D surfaces.

Keywords— Imaging Systems, Multistatic radar system, Security scanning.

References:

1. D. Sheen, D. McMakin, and T. Hall, “Three-Dimensional MillimeterWave Imaging for Concealed Weapon Detection,” IEEE T. Microwave Theory and Techniques, vol. 49, no. 9, pp. 1581-1592, Sept. 2001.

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Northeastern University

ALERT
AWARENESS AND LOCALIZATION
OF EXPLOSIVES-RELATED THREATS

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EuCAP Lisbon, Portugal, April 15, 2015

Outline

- State of the art
- Multistatic radar
- Blade beam reflector
- Elliptical Toroidal Reflector
- Simulation Results
- Experimental Results

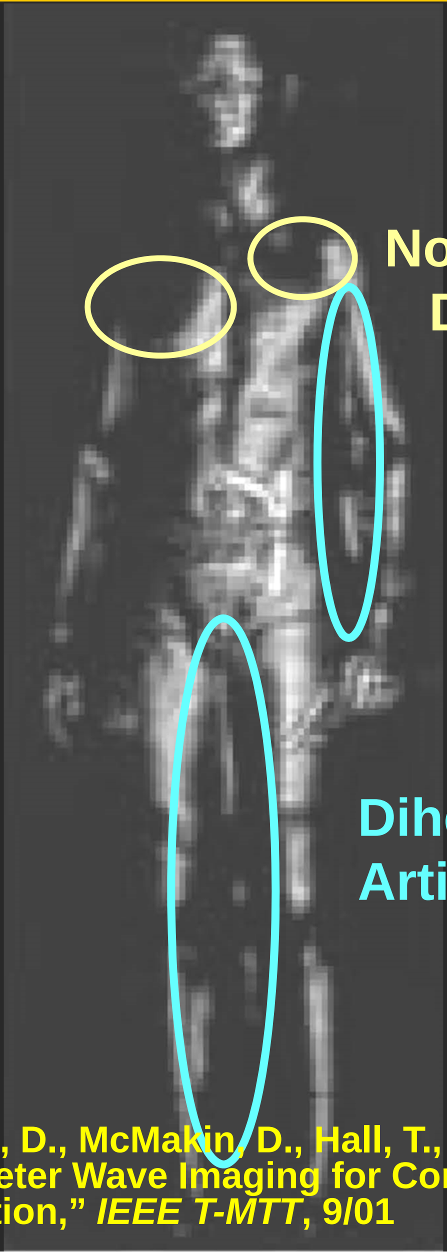
Mm-Wave Imager: Current State-of-the-Practice – L3 ProVision

- Detects many types of materials based on shape (metallic and non-metallic): liquids, gels, plastics, metals, ceramics

L3 ProVision

- Limitations
  - “Dead Spots”
  - No chemical info
  - Limited views
  - Poor penetration through leather and metallic clothing
  - No penetration through skin or into body cavities

State of the art



Current mm-wave scanners are based on monostatic radar:

•Presents specular reflection only – no depth encoding

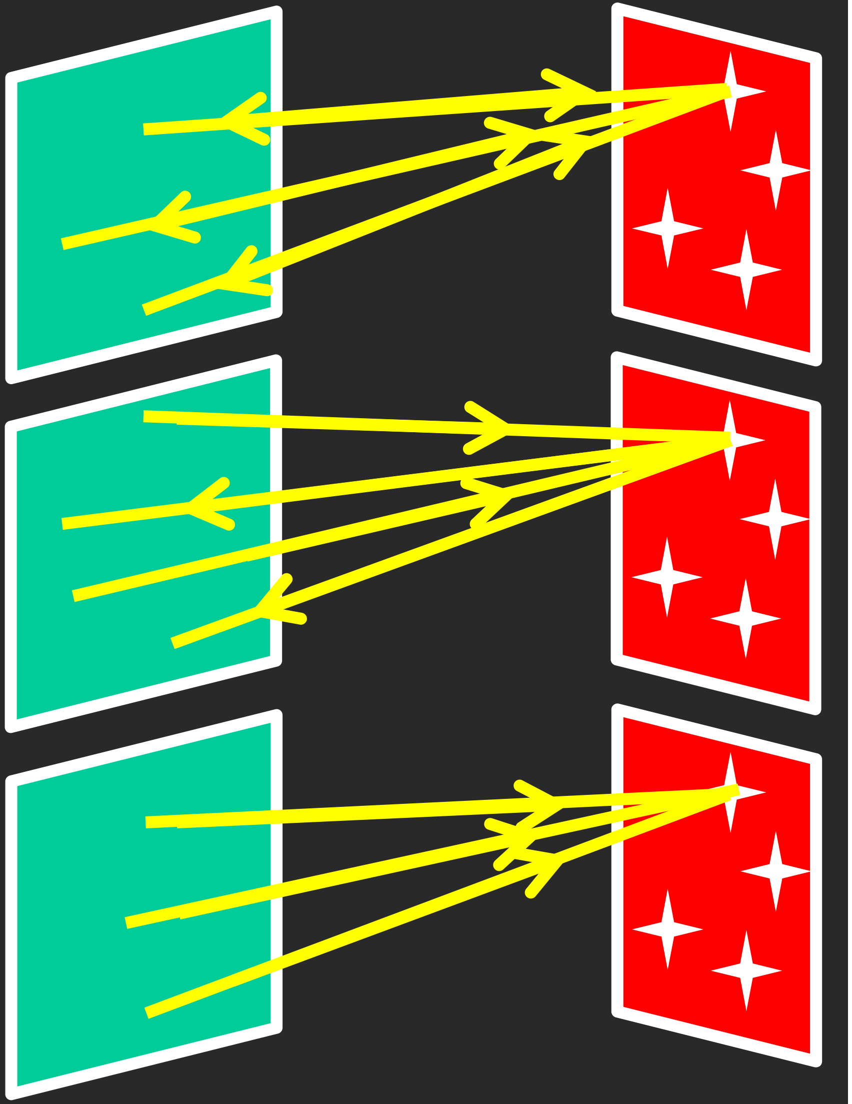
•Uses Fourier inversion – fast, but not best for close imaging.

•Shows shapes of metallic objects, but does not fully consider reverse imaging of weak dielectrics (i.e. explosives).

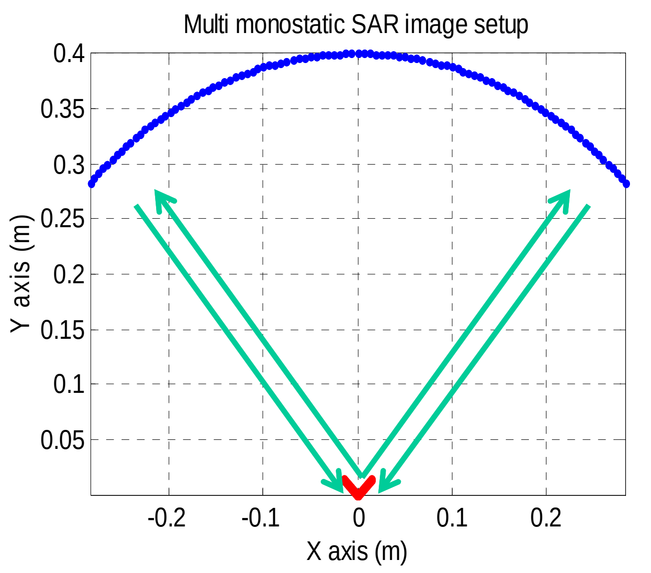
Sheen, D., McMakin, D., Hall, T., "Three-Dimensional Millimeter Wave Imaging for Concealed Weapon Detection," *IEEE T-MTT*, 9/01

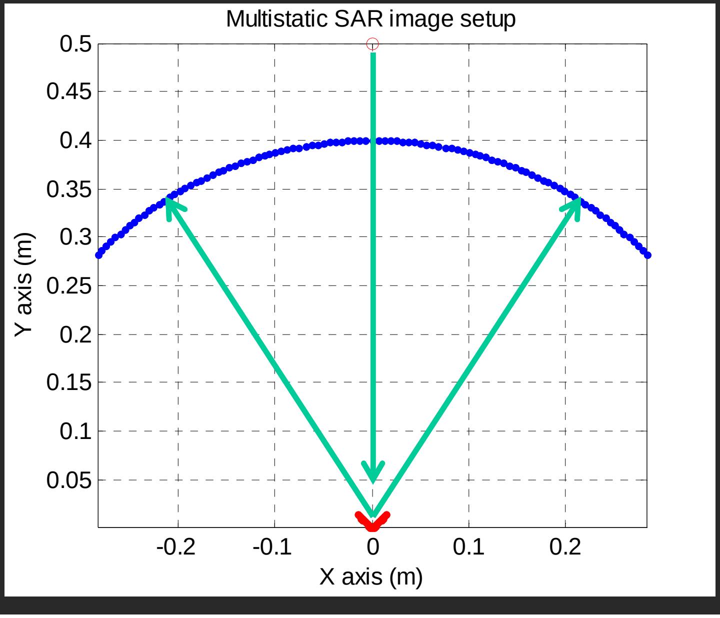
Monostatic / Multistatic Radar

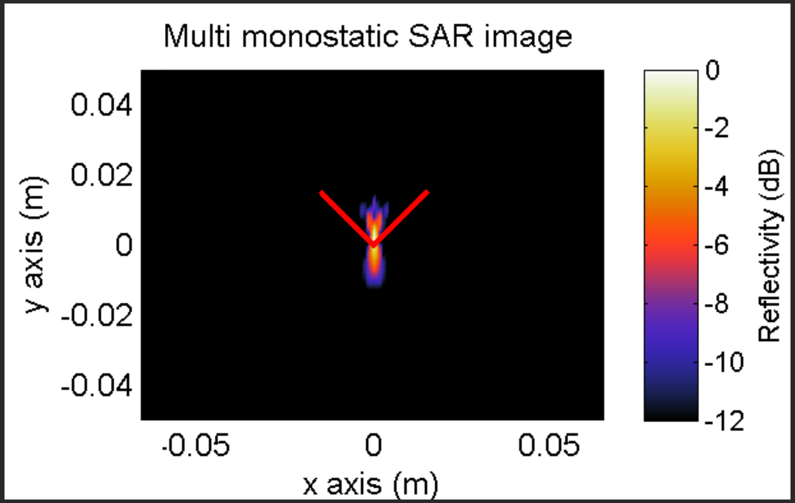
- Monostatic
  - Multi-monostatic
- Bistatic
  - Multi-bistatic
- Multistatic

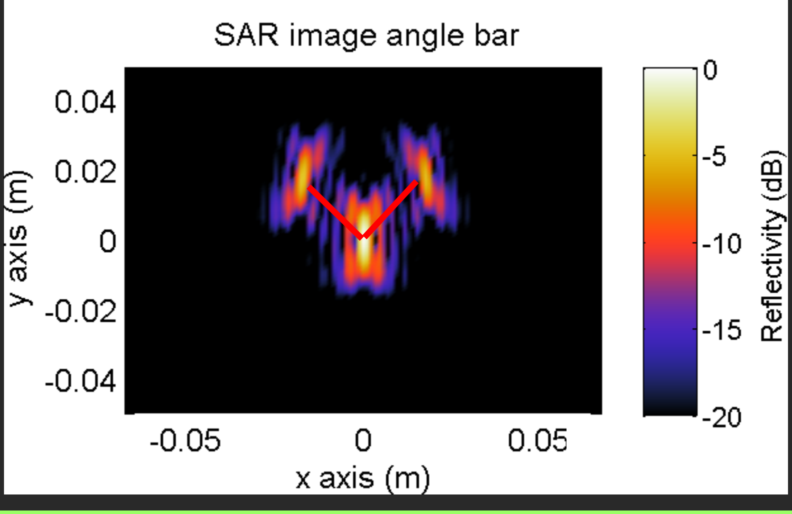


Multi-Monostatic vs. Mulitstatic Mm-Wave Radar Imaging Example


Multi monostatic SAR image setup
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Y axis (m)
-0.2
-0.1
0
0.1
0.2
X axis (m)


Multistatic SAR image setup
0.5
0.45
0.4
0.35
0.3
0.25
0.2
0.15
0.1
0.05
Y axis (m)
-0.2
-0.1
0
0.1
0.2
X axis (m)



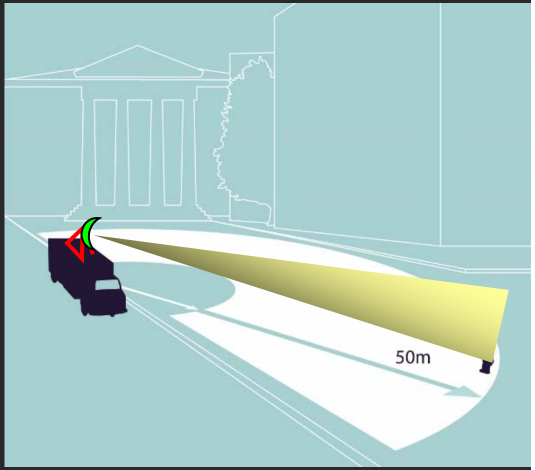


Monostatic: Dihedral images to a point

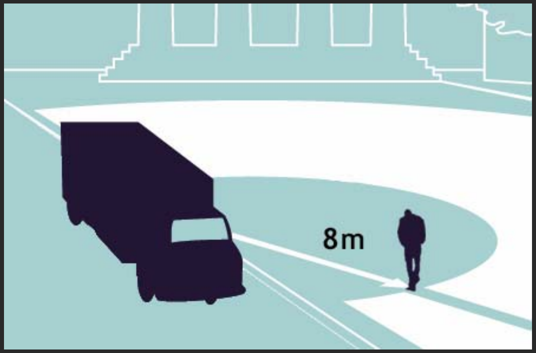
Multistatic: Dihedral images to correct corner scatterer

Detection Regimes

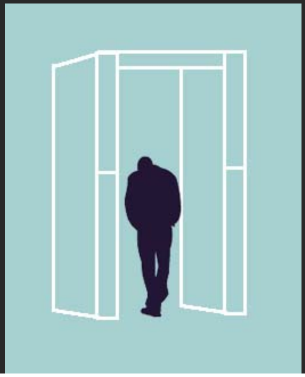
- Distant targets (10 m to >100 m),
  - Stand-off detection of hazards
  - Far enough away to minimize threat



- Mid-range targets (3 to 10m)
  - Enhanced sensing discrimination
  - Not explicitly surrounding target



- Intimately near targets (< 3 m)
  - Non-invasively examined
  - Mostly portal sensors



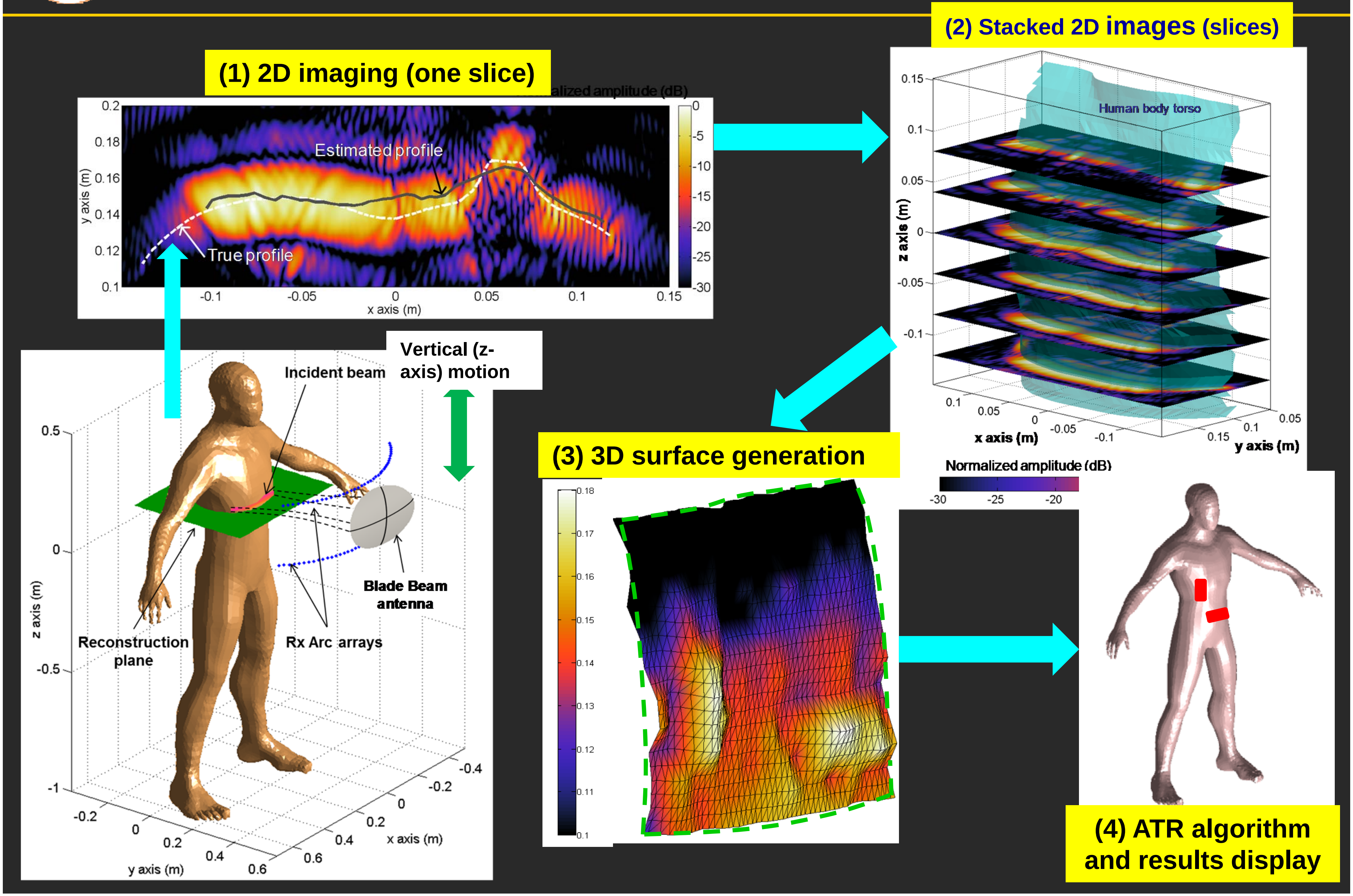
Overview & Technical Approach

- **Custom designed elliptical torus reflector allows multiple overlapping beams for focused wide-angle illumination to speed data acquisition and image inclined body surfaces.**

- **Multiple transmitters provide horizontal resolution and imaging of full 120 deg. of body.**

- **Multistatic Tx and Rx array sensing avoids dihedral artifacts from body crevices and reduces non-specular drop-outs.**

Operational Concept: Stack 2D Slices to Generate 3D Surface – Minimize Hardware, Simplify Calculation



(1) 2D imaging (one slice)

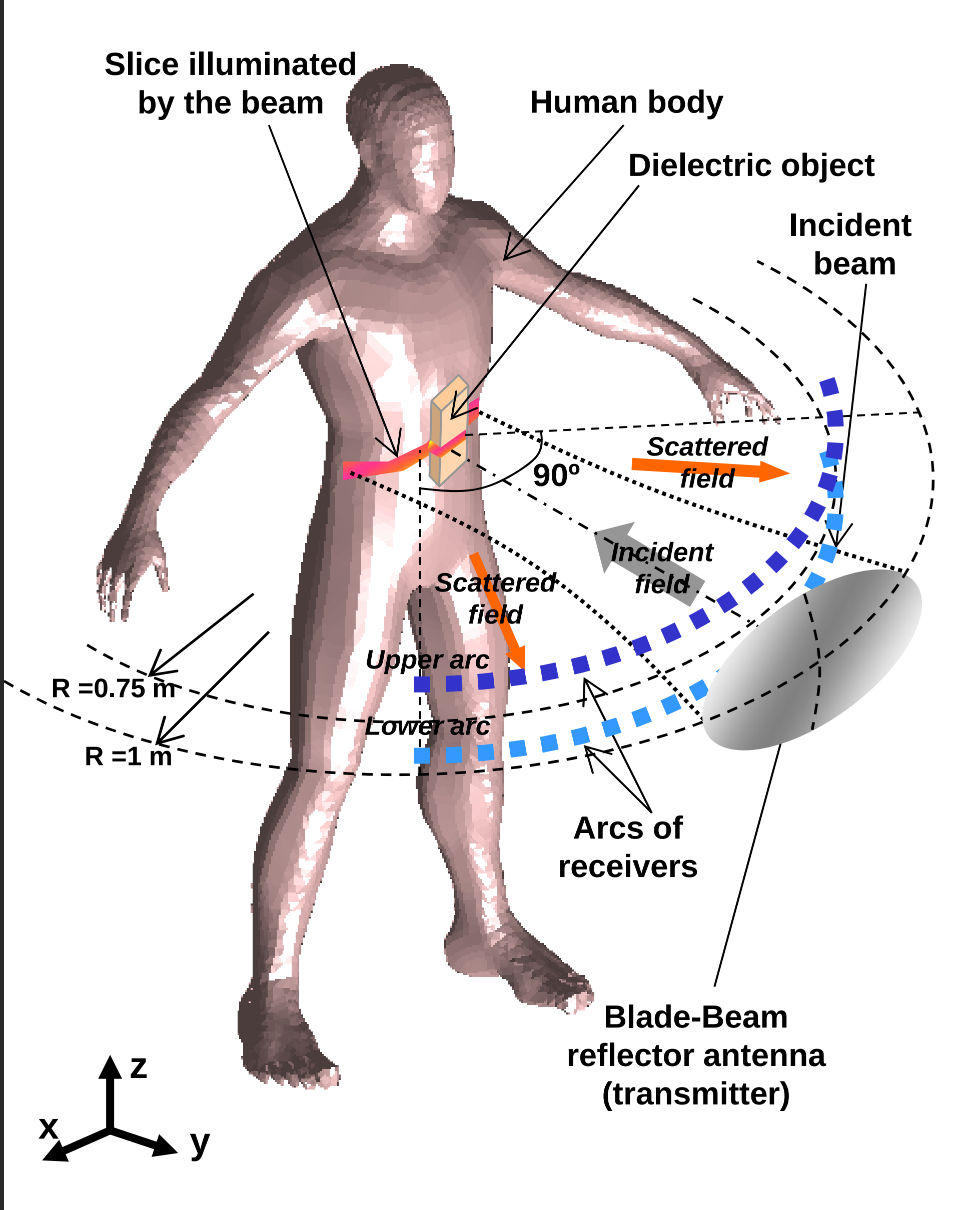
(2) Stacked 2D images (slices)

(3) 3D surface generation

(4) ATR algorithm and results display

...alized amplitude (dB)
Estimated profile
True profile
y axis (m)
x axis (m)
0.2
0.18
0.16
0.14
0.12
0.1
-0.1
-0.05
0
0.05
0.1
0.15
0
-5
-10
-15
-20
-25
-30
Incident beam
Vertical (z-axis) motion
Blade Beam antenna
Reconstruction plane
Rx Arc arrays
z axis (m)
0.5
0
-0.5
-1
-0.2
0
0.2
0.4
0.6
y axis (m)
-0.4
-0.2
0
0.2
0.4
0.6
x axis (m)
Human body torso
z axis (m)
0.15
0.1
0.05
0
-0.05
-0.1
x axis (m)
0.1
0.05
0
-0.05
-0.1
y axis (m)
0.15
0.1
0.05
Normalized amplitude (dB)
-30
-25
-20
0.18
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1

System setup: vertically Moving Focusing Reflector Antenna Trans./Arc Array Rec.


Slice illuminated by the beam
Human body
Dielectric object
Incident beam
Scattered field
90°
Incident field
Scattered field
Upper arc
Lower arc
R =0.75 m
R =1 m
Arcs of receivers
Blade-Beam reflector antenna (transmitter)
z
x
y

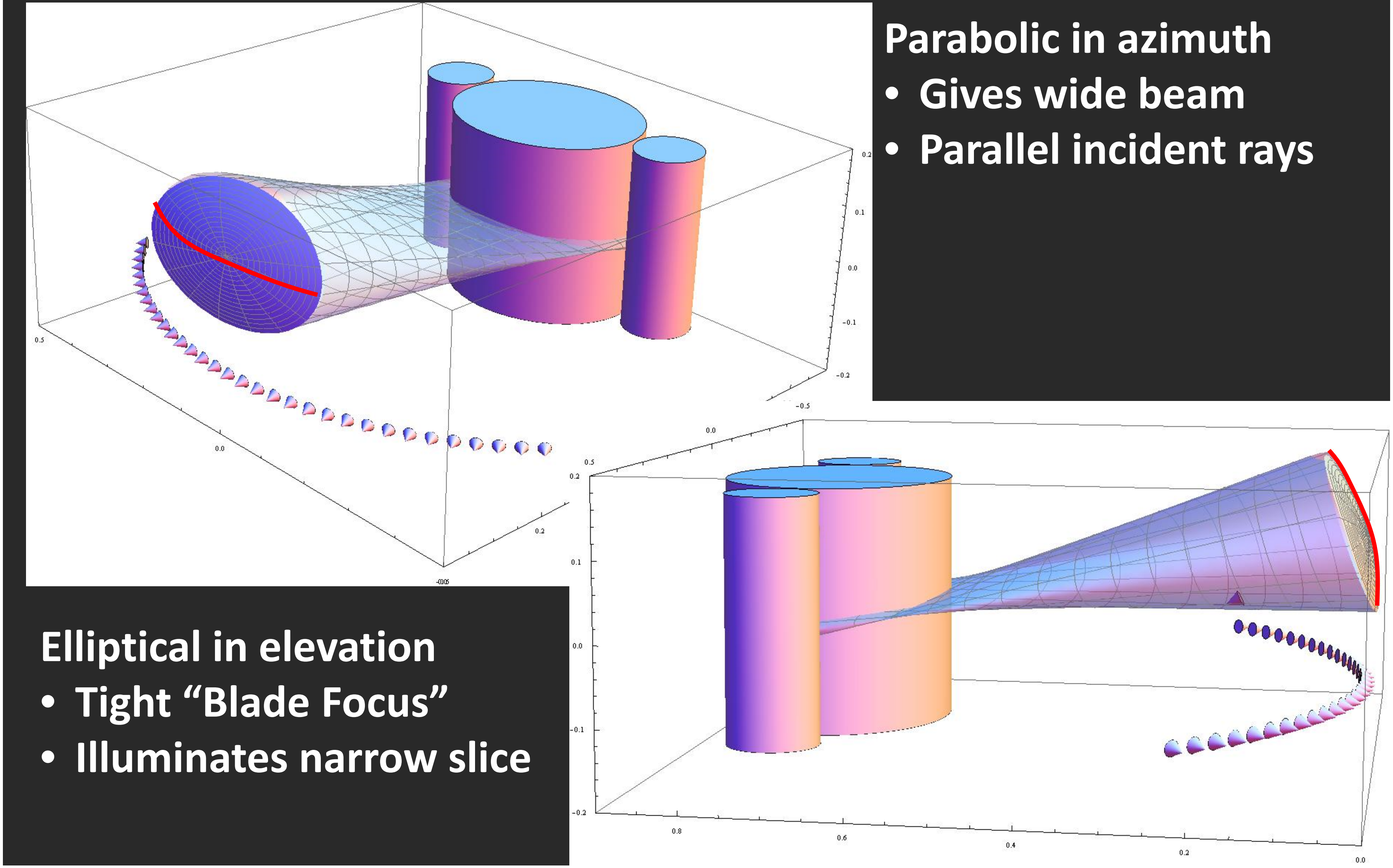
One transmitter

- Moves up/down
- Focuses on thin slice
- Allows multiple 2D processing
- Minimal motion artifacts

Arc Receiver

- Quarter circle
- Sparse element positions
- Moves up/down with transmitter
- Multistatic: no dihedral artifacts

System setup: Specially Designed Elliptical Parabolic Reflector Focuses to a Thin Slice on Body


0.2
0.1
0.0
-0.1
-0.2
-0.5
0.5
0.0
0.2
0.5
0.0
0.2
0.1
0.0
-0.1
-0.2
0.8
0.6
0.4
0.2
0.0

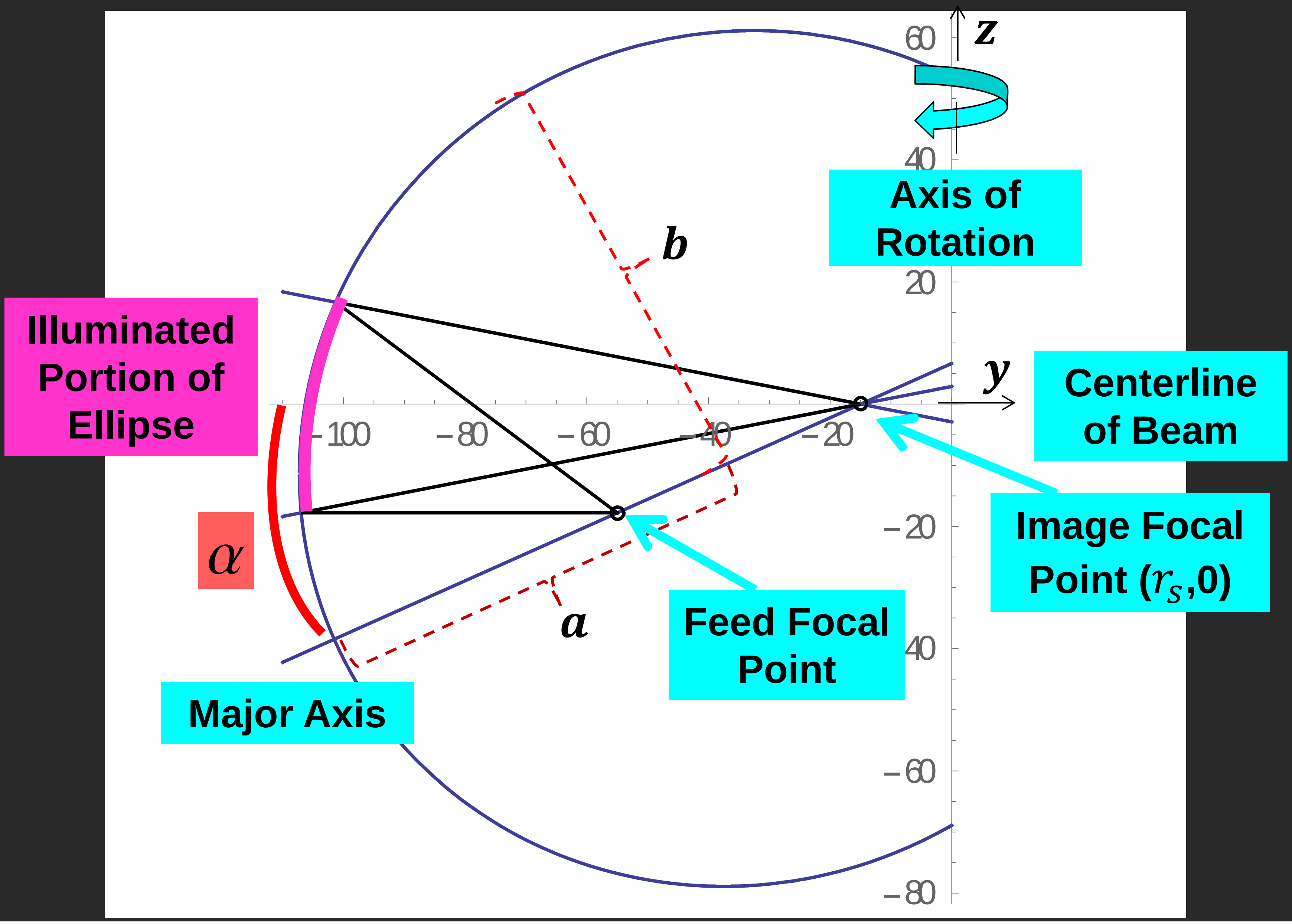
Parabolic in azimuth

- Gives wide beam
- Parallel incident rays

Elliptical in elevation

- Tight “Blade Focus”
- Illuminates narrow slice

Toroidal Reflector – Offset Elliptical Profile (side view)



60
40
20
−20
−40
−60
−80
−100
−80
−60
−40
−20
z
y
b
a
α

Axis of Rotation

Illuminated Portion of Ellipse

Centerline of Beam

Image Focal Point $(r_s,0)$

Feed Focal Point

Major Axis

$\vec{r}_1 = x\hat{x} + y\hat{y} + z\hat{z}$

Toroidal Reflector Equations

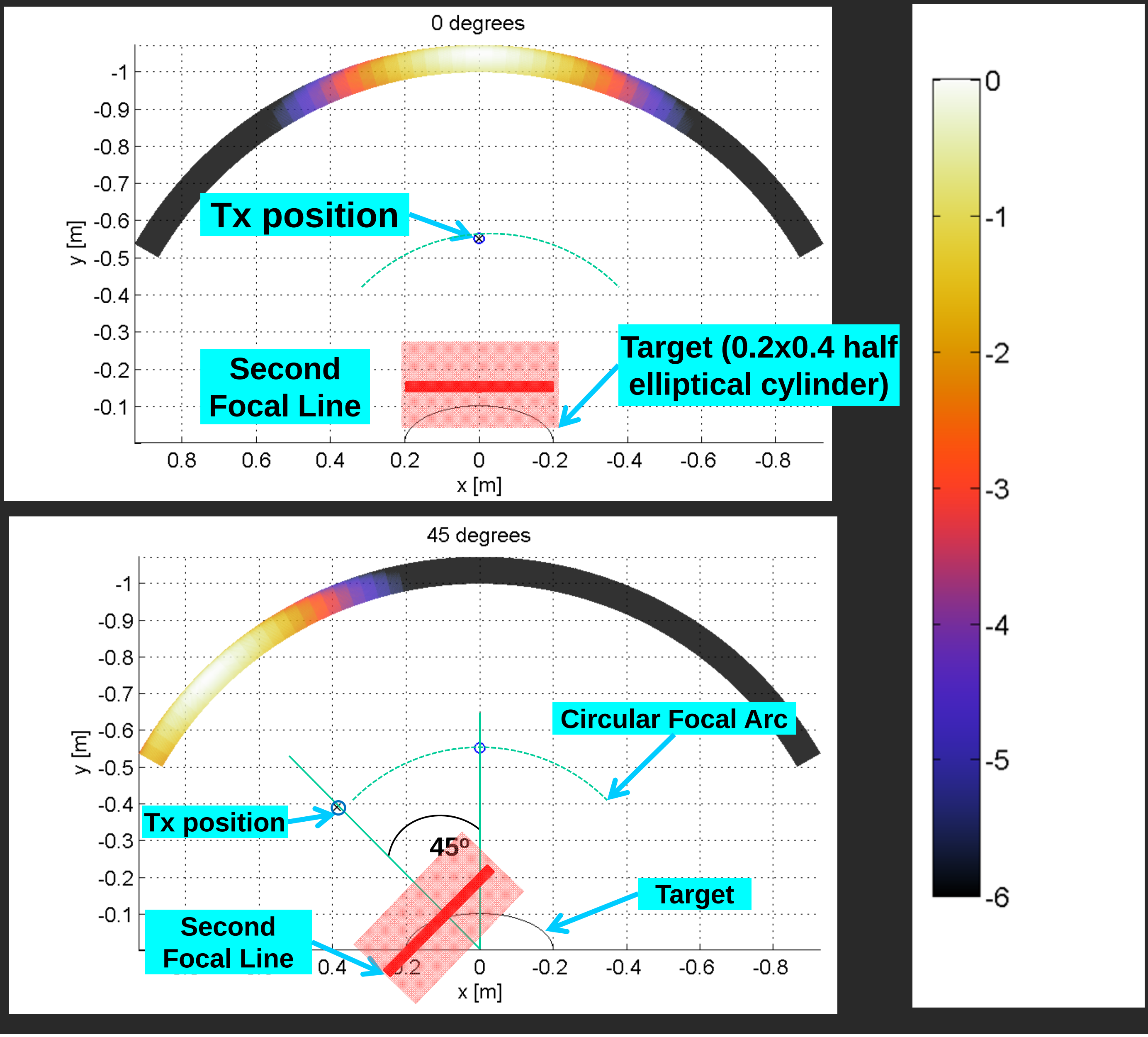
$$Az^2 + By^2 + Czy + Dz + Ey + F = 0$$

$$A = -b^2 - c^2 \cos^2 \alpha$$
$$B = -a^2 + c^2 \cos^2 \alpha$$
$$C = -2c^2 \cos \alpha \sin \alpha$$
$$\mathrm{D} = 2c(b^2 + c\, r_s \cos \alpha) \sin \alpha$$
$$\mathrm{E} = 2\left(a^2 r_s - c \cos \alpha\, (b^2 + c\, r_s \cos \alpha)\right)$$
$$F = -a^2 {r_s}^2 + (b^2 + c\, r_s \cos \alpha)^2$$

$$a^2 = b^2 + \mathrm{c}^2$$

- **Secondary focus at (r_s, 0)**
- **Primary focus at *(r_s-2c $\cos \alpha$, -2c $\sin \alpha$)***
- **Tilt relative to y-axis α**

Reflector View from Above for Two Feed Positions 0 and 45 deg.



Tx position

Second Focal Line

Target (0.2x0.4 half elliptical cylinder)

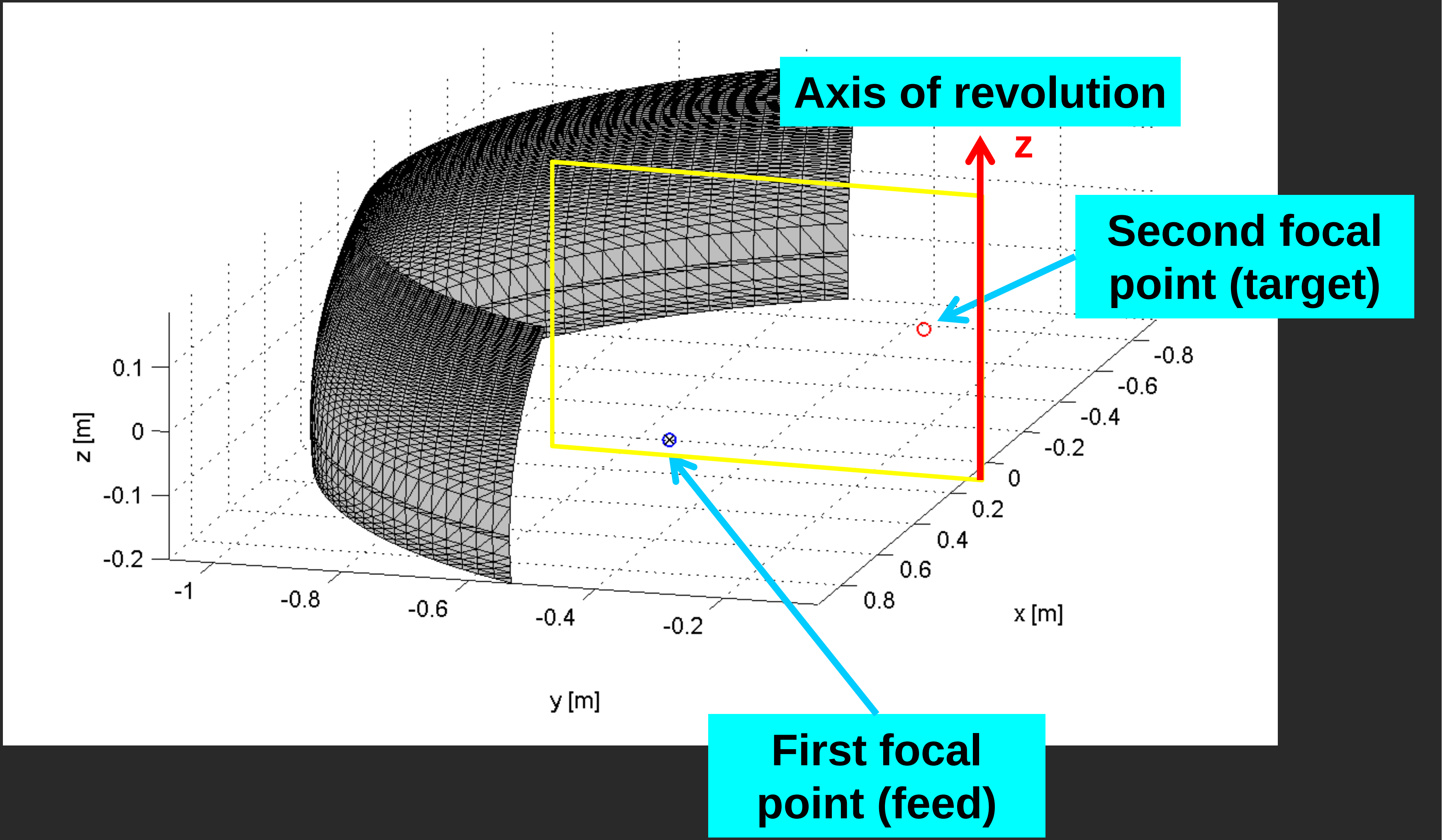
Circular Focal Arc

Tx position

Second Focal Line

Target

Elliptical Torus Reflector – Surface of Revolution Allows Multiple Scanned Transmitters

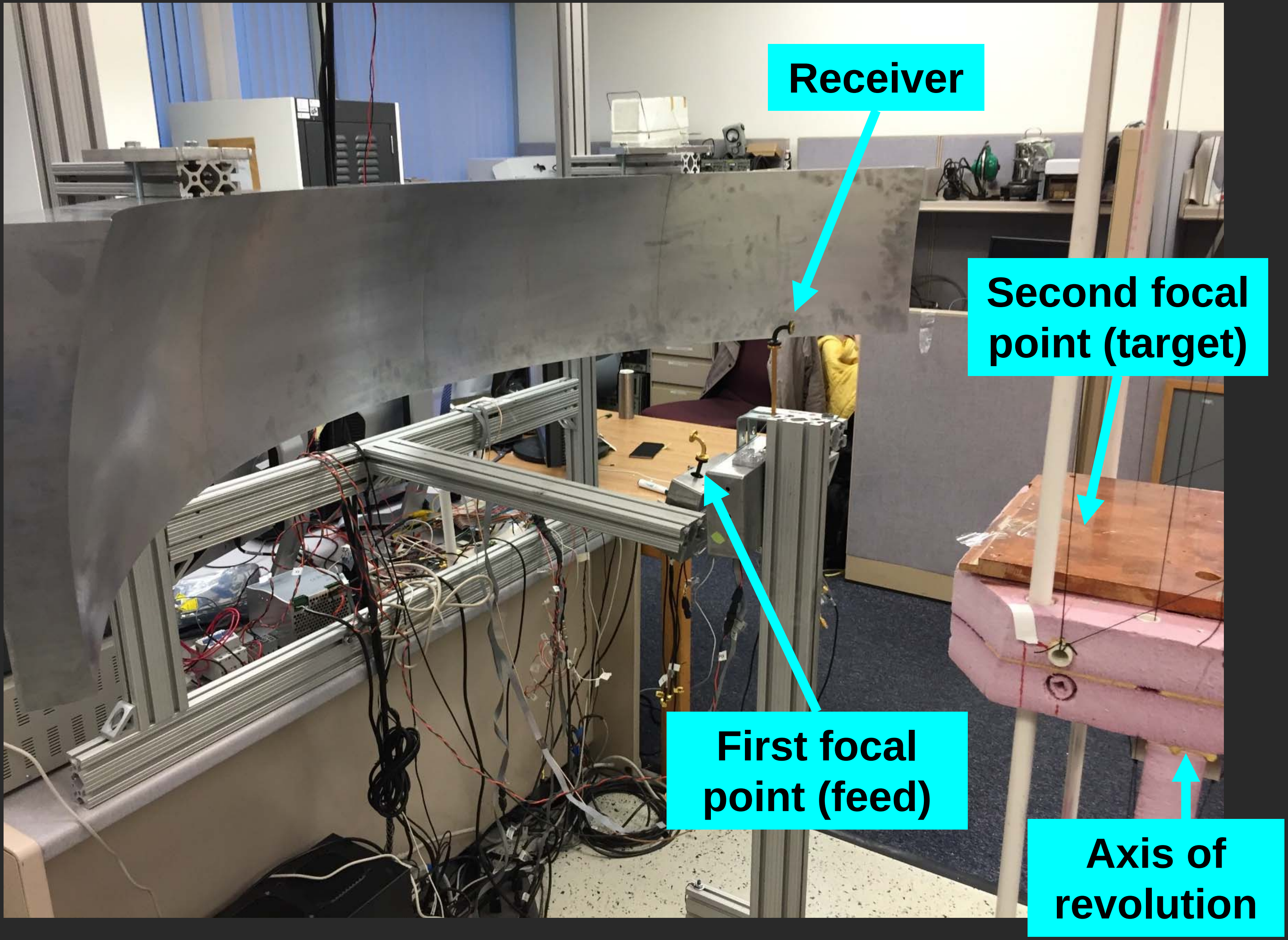


Axis of revolution

Second focal point (target)

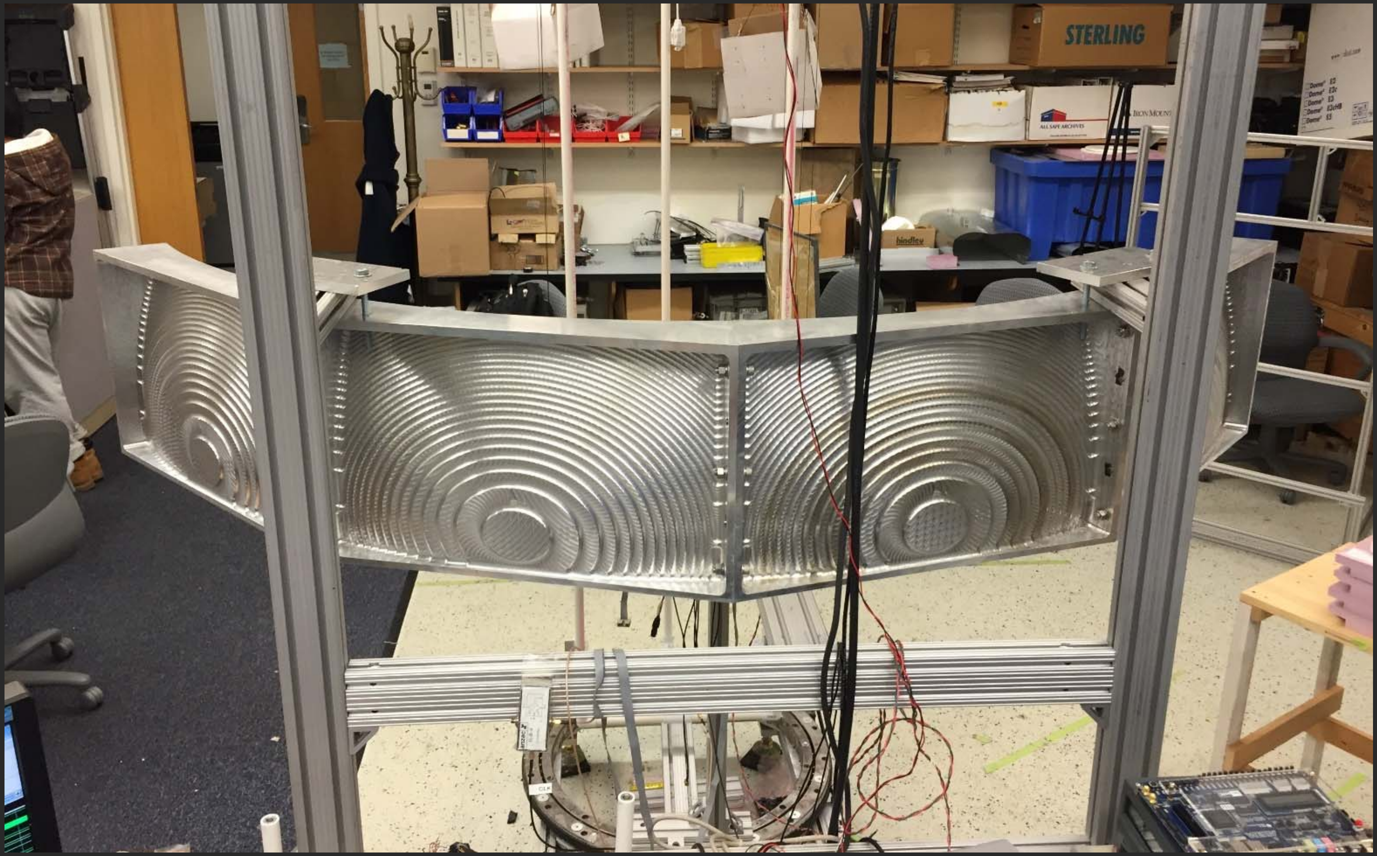
First focal point (feed)

Fabricated Torus Reflector


Receiver
Second focal point (target)
First focal point (feed)
Axis of revolution

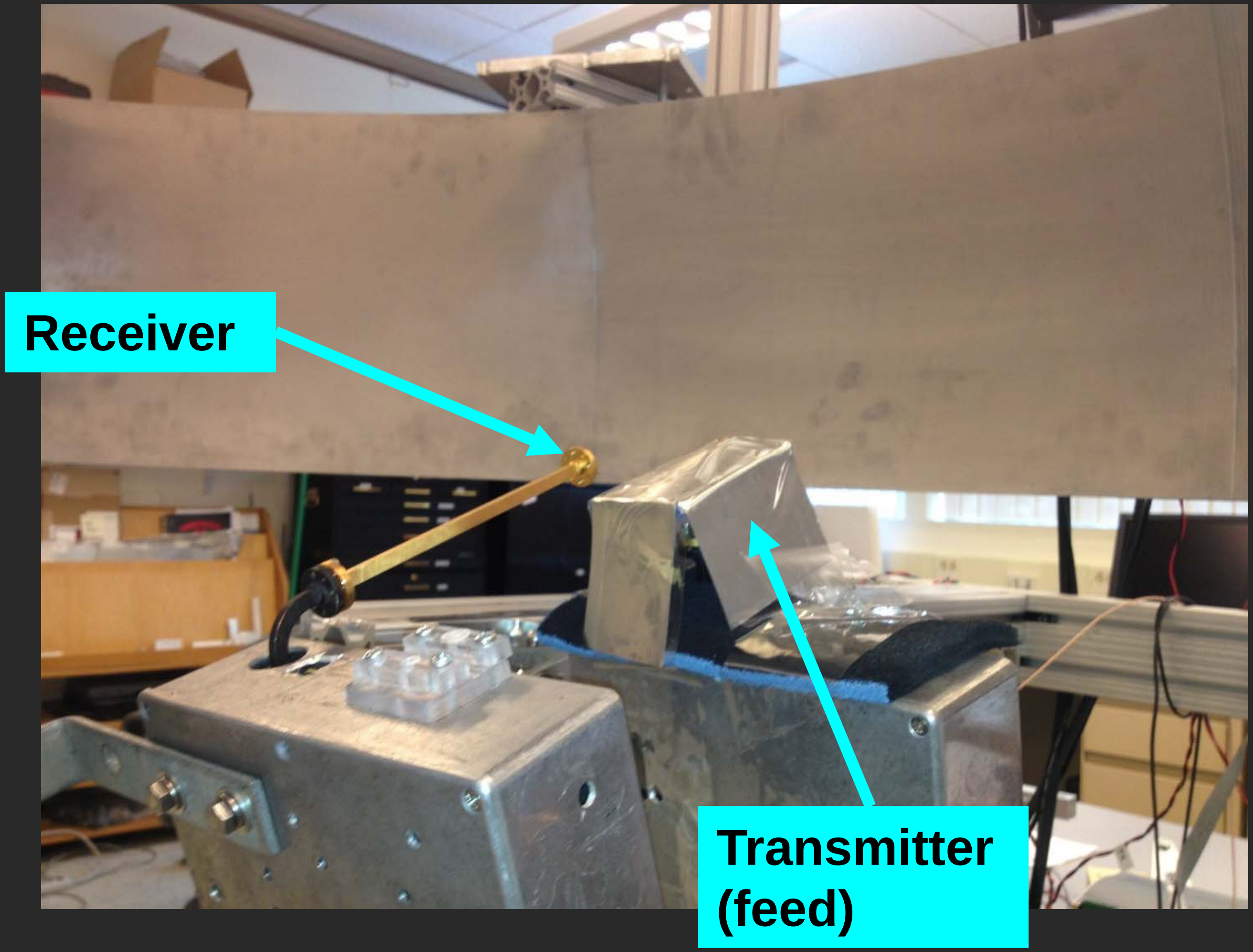
Aluminum Reflector Machined with CNC Milling Machine – 0.0001m Surface Tolerance

- 4 Identical panels
- 8 kg per panel
- Elliptical vertical profile X circular arc horizontal profile



Back view, showing rough cuts for weight reduction

Torus Reflector Configured with Both Transmit and Receive Elements on Focal Arc, Facing Torus


Receiver
Transmitter
(feed)

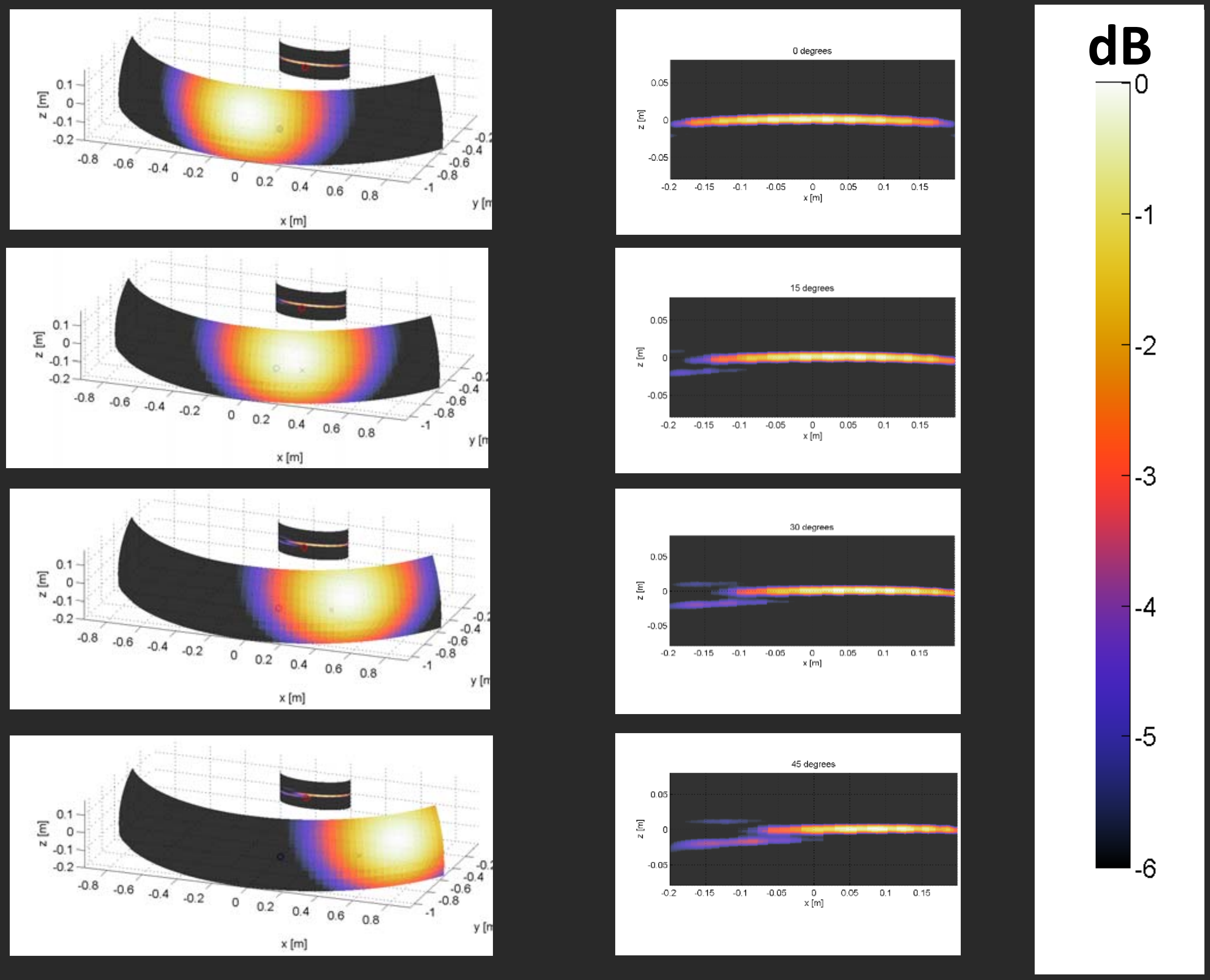
Reflector and Elliptical Cylinder Target Illumination for Scanned Transmitters

0°

15°

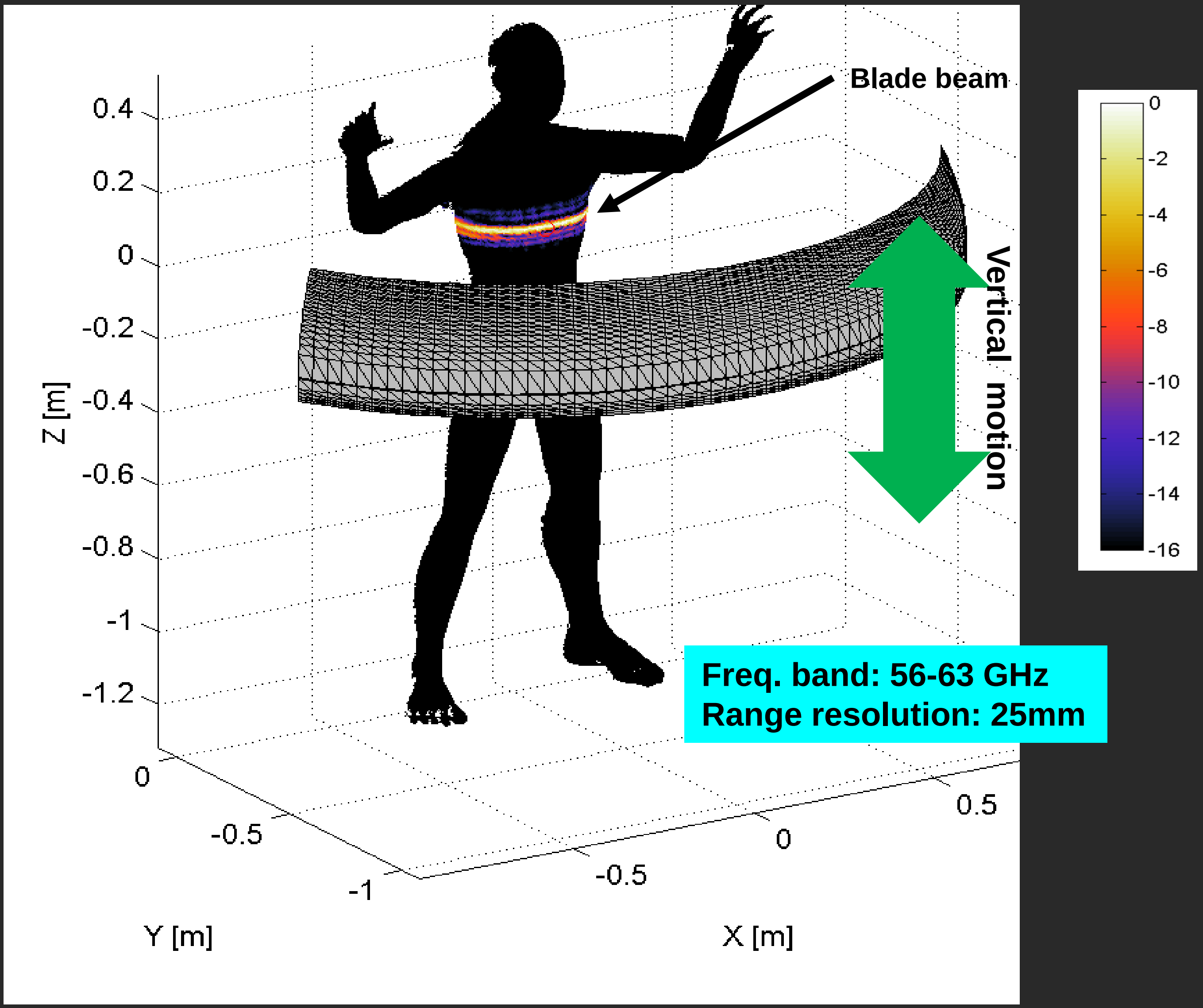
30°

45°

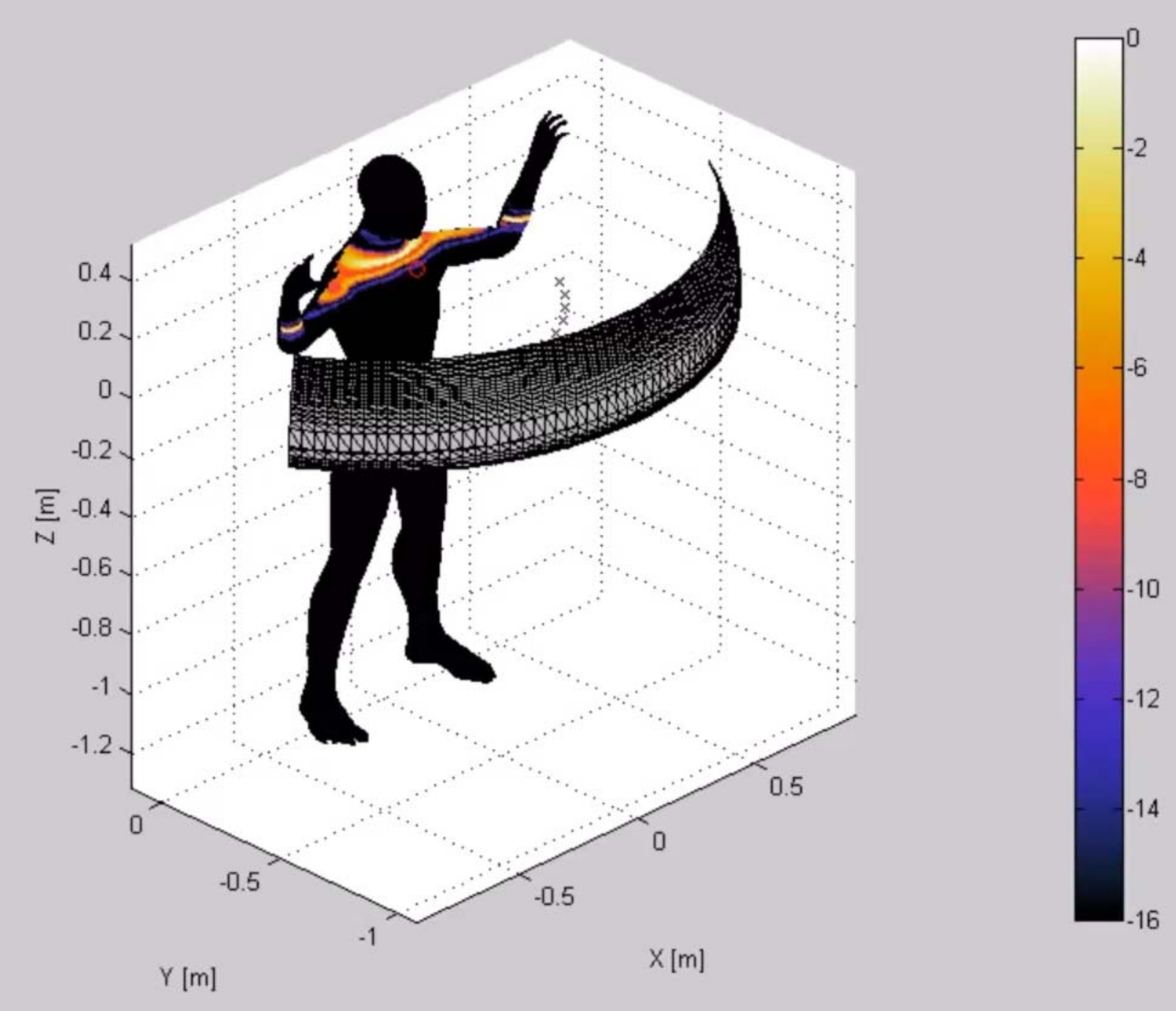


Tx Position **Reflector Illumination** **Target Illumination**

Computed Illumination from Vertically Translating Toroidal Reflector

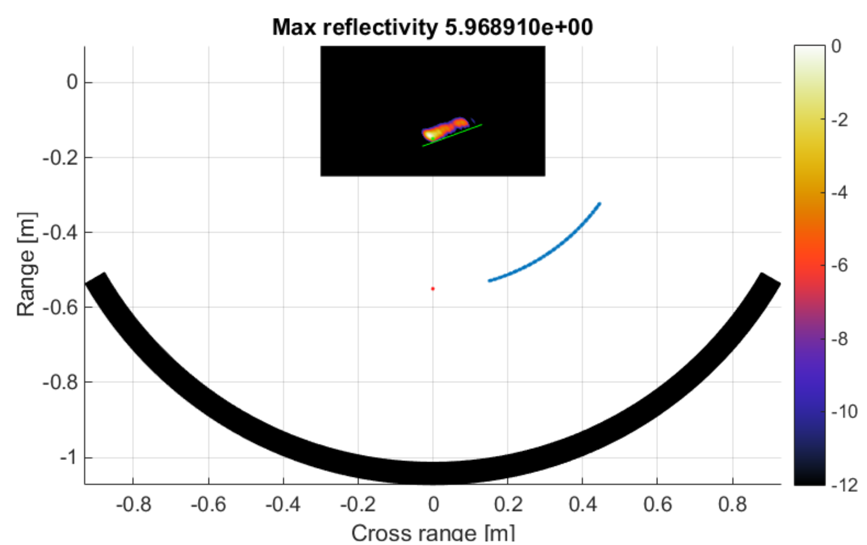


Freq. band: 56-63 GHz
Range resolution: 25mm



0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
-1
-1.2
Z [m]
0
-0.5
-1
Y [m]
0.5
0
-0.5
X [m]
0
-2
-4
-6
-8
-10
-12
-14
-16

Multistatic Imaging with Torus Reflector – 20 deg. Inclined Metal Box, Half Receiver Arc



Ground Truth in Green

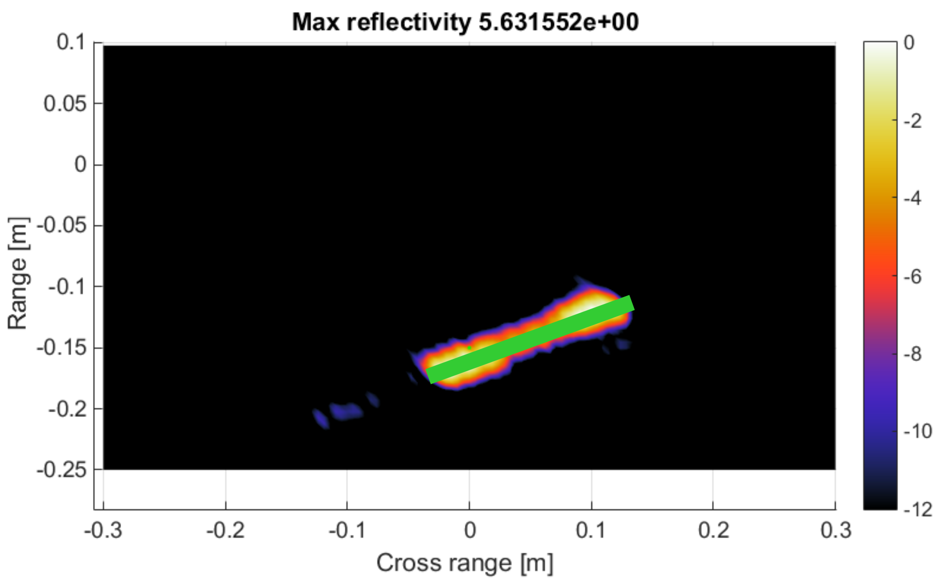


Image from Measured Data

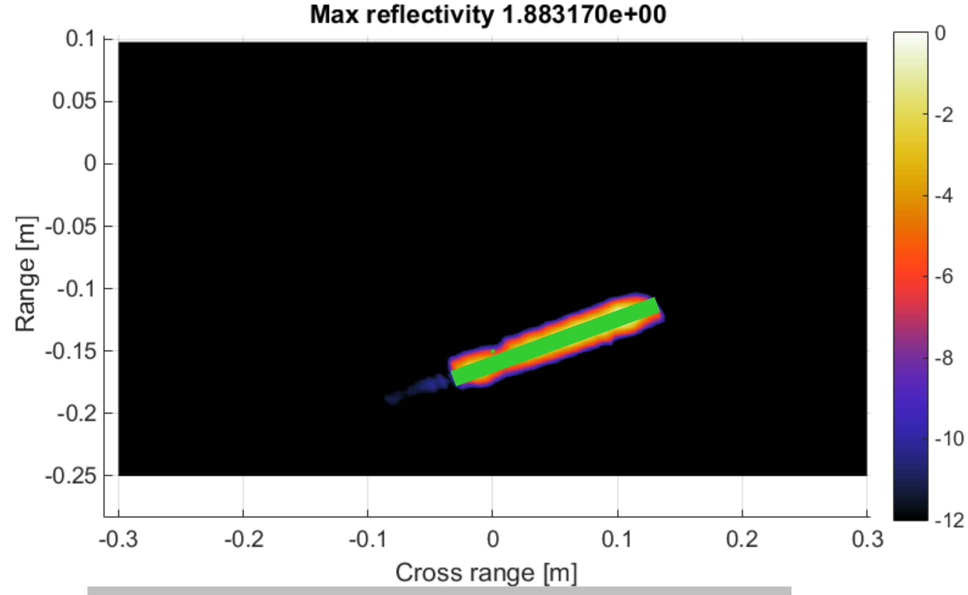
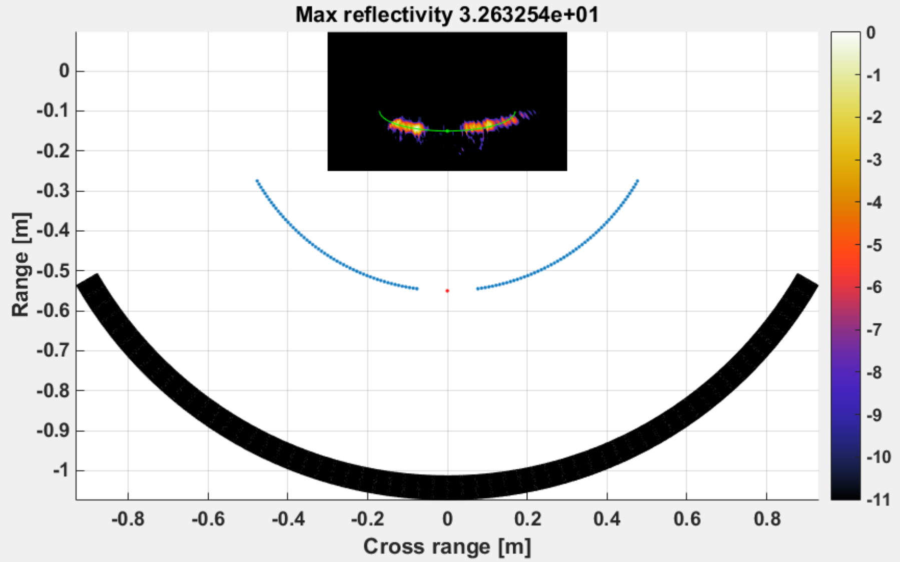


Image from Modeled Data

Torus Reflector – Metal Torso Simulant Measured over Left & Right Half Arcs



Ground Truth in Green

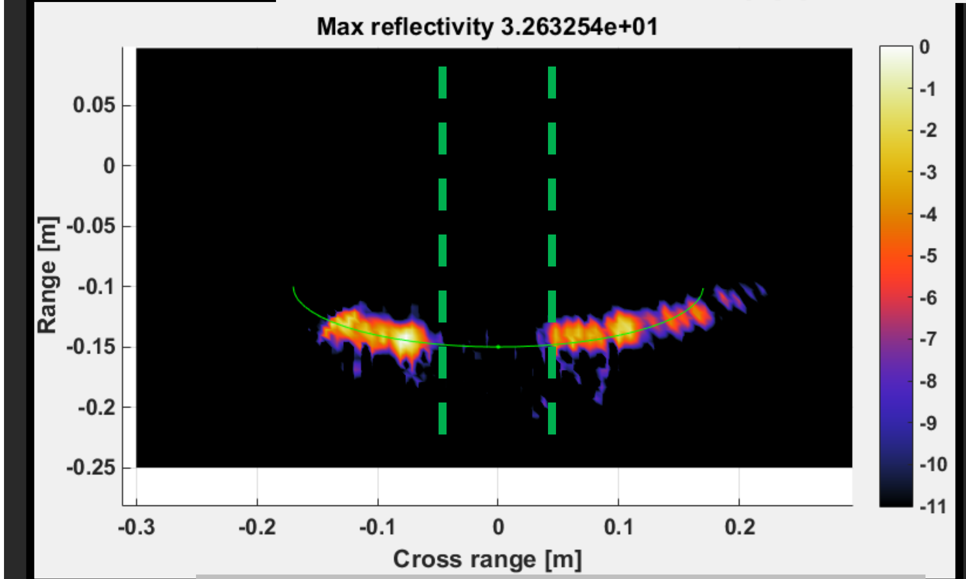


Image from Measured Data

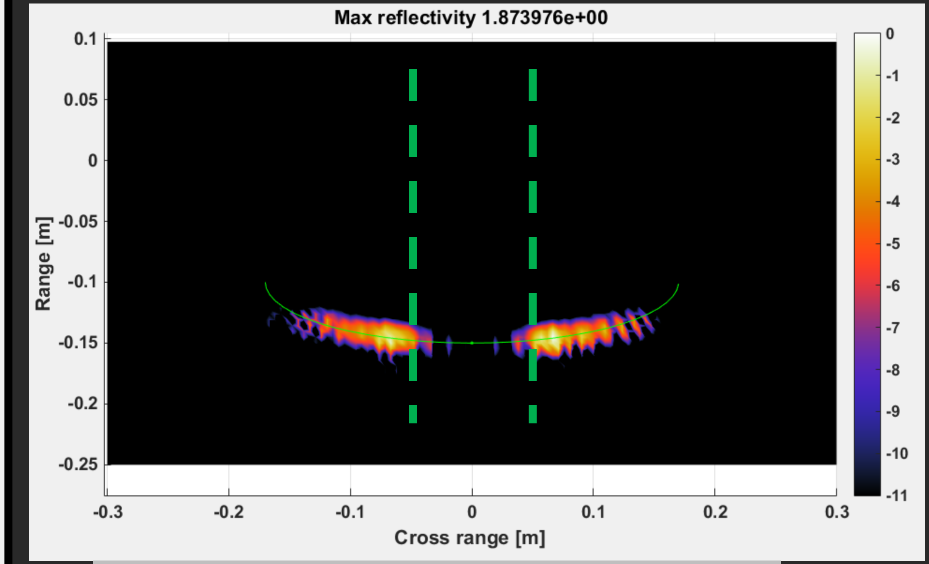
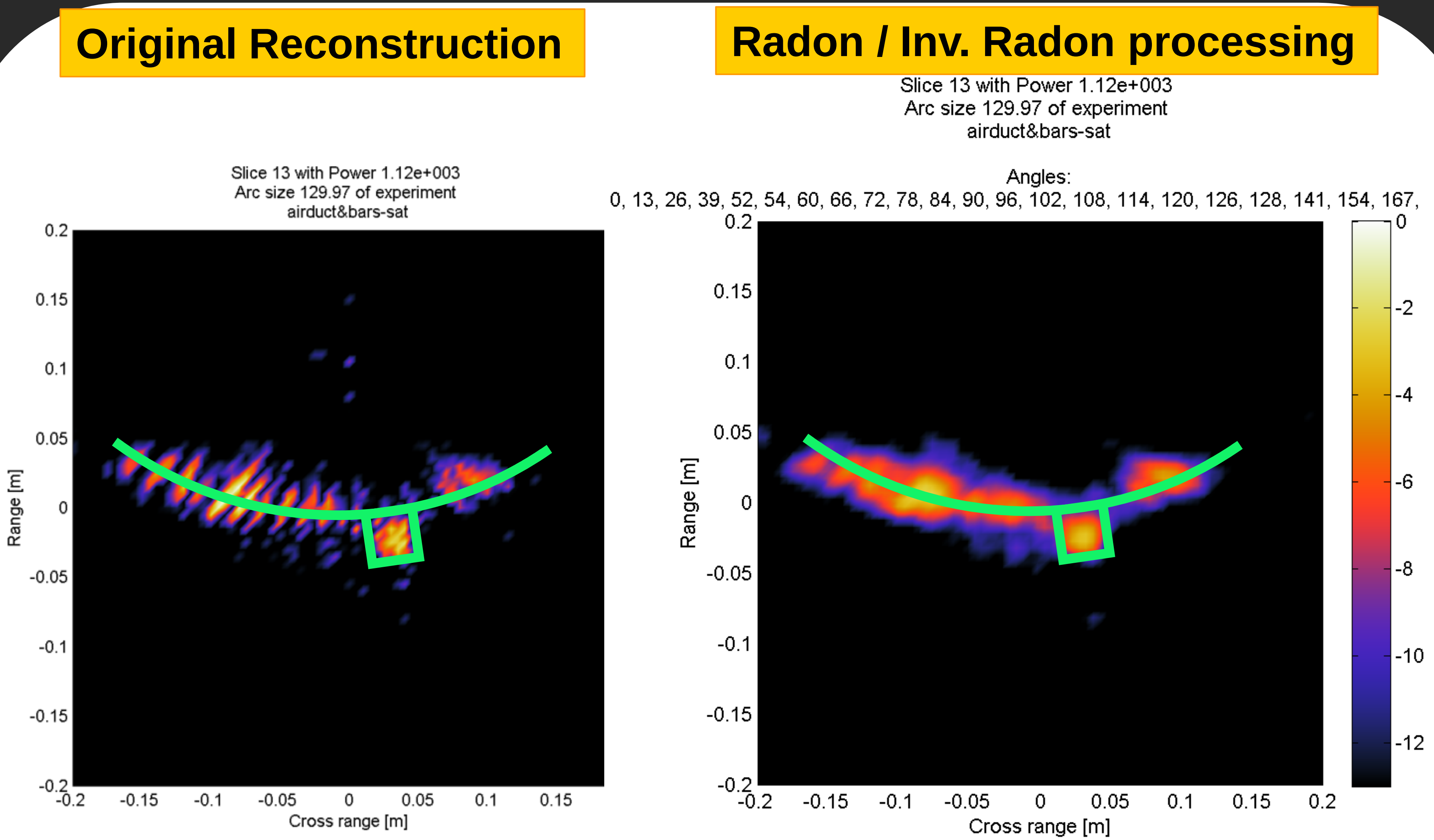


Image from Modeled Data

SAR Reconstruction of Mm-Wave Radar Measurements



Curved metallic torso surrogate with attached square pipe

Conclusions

- Extension of Blade Beam Reflector into Elliptical Torus for multiple overlapping high quality beams
- Illumination and receiver focusing on narrow slice for fast computation
- Fabrication, testing, optimization of wideband 60GHz multistatic radar
- Novel reflector antenna, stacked 2D reconstruction, and fast inversion for real time processing
- Minimal artifacts from dihedrals, full depth information and advanced visualization

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